学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Effect of increased near-fault fracture stiffness on seismic source parameters of induced seismicity
(断層近傍のき裂剛性増加が誘発地震の震源パラメータに与える影響)

Induced seismicity associated with underground resource extraction, geothermal development, and fluid-injection operations poses significant risks to mine safety and infrastructure. In deep mines, seismic events often occur not only near active excavations but also at considerable distances, largely due to the complex mechanical behavior and the heterogeneous stress conditions within natural structures. Although mitigation methods such as microseismic monitoring, destress blasting, hydraulic fracturing, and traffic-light systems are widely applied, their effectiveness remains limited because they do not explicitly consider the strong stress heterogeneity caused by these geological structures.

Especially faults, consisting of a narrow core and a wider damage zone with densely fractured rock, play a central role in stress redistribution and seismic slip. Prior theoretical, numerical, and experimental studies suggest that increasing the stiffness of surrounding rock can reduce radiated seismic energy and thus suppress seismic intensity. However, a comprehensive framework that integrates experimental evidence of damage-zone mechanical heterogeneity with multiscale numerical modeling is still lacking. In particular, the internal stress-strain states within fault damage zones and their implications for stiffness-based mitigation strategies remain insufficiently understood, mainly due to the difficulty of characterizing fractures embedded within the rock mass. To address these gaps, this study examines the mechanical complexity and heterogeneous stress-strain states within fault damage zones through a new experimental method, while investigating the effectiveness of enhancing near-fault fracture stiffness in controlling induced seismicity using two complementary numerical modeling approaches. The specific contents of each chapter are as follows:

Chapter 1 introduces the fundamental background and significance of induced seismicity in mining and other subsurface engineering fields. The limitations of existing mitigation approaches are reviewed. This chapter also presents the objectives and overall structure of the thesis.

Chapter 2 establishes the theoretical basis for a stiffness-based mitigation strategy using the slip-weakening framework. The relationship between system stiffness, fault slip behavior, and seismically radiated energy is examined, and a parametric analysis is conducted to verify the theoretical feasibility of reducing seismic intensity through fracture stiffness enhancement. This chapter provides the theoretical foundation for the subsequent numerical investigations.

Chapter 3 presents experimental investigations to demonstrate the internal mechanical complexity of fault damage zones. An X-ray computed tomography (CT)- and digital image correlation (DVC)-based experimental methodology using 3D-printed rock-like specimens is developed to visualize and quantify heterogeneous internal strain states within damage zone analogues. The experimental results are used to characterize deformation patterns and strain distributions within fractured media, thereby

providing physical evidence of damage zone heterogeneity and a realistic basis for the numerical modeling approaches adopted in the subsequent chapters.
Chapter 4 develops a discrete element method (DEM) model that explicitly represents a damage zone using a statistically generated discrete fracture network (DFN). Fractures are modeled as disk-shaped discontinuities with independently assigned normal and shear stiffness. Parametric studies are conducted to investigate the effects of fracture stiffness, as well as the individual contributions of normal and shear stiffness, on fault slip process and seismic source parameters. This chapter provides fracture-scale insight that supports the stiffness-based mitigation strategy.
Chapter 5 introduces a mine-scale continuum numerical model based on crack tensor theory, in which the heterogeneous damage zone is represented as an equivalent anisotropic continuum. To overcome the computational limitations of DEM for damage zones with dense fractures, this model reproduces heterogeneous in-situ stress conditions and mining-induced fault slip, enabling systematic evaluation of stiffness-based mitigation effectiveness at the macroscopic scale. Using this framework, the influence of fracture stiffness, fracture density and distance from the fault on seismic source parameters are quantitatively studied.
Chapter 6 provides an overall synthesis of the main outcomes of this thesis including discussion on their implications for seismic hazard mitigation in deep underground settings. The benefits and limitations of the stiffness-based approach, as well as those of the numerical and experimental methods used, are also summarized. Furthermore, this chapter outlines future research directions and potential applications of stiffness enhancement in practical mine design and seismic risk management.